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THE INFLUENCE OF HEAVY METAL POLLUTION ON THE PIGMENT CONTENT IN THE ASSIMILATION APPARATUS OF POPLAR CULTIVARS IN THE CONDITIONS OF THE IRON ORE REGION

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Abstract

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We carried out studies of the translocation of heavy metals in the soils of Kryvyi Rih. The peculiarities of the accumulation of heavy metals in the assimilation apparatus of seven poplar cultivars were clarified. The maximum rates of translocation of heavy metals were detected at the monitoring site of the industrial site of Northern Iron Ore Dressing Combine (henceforth referred to as Pivnichnyi HZK or PivnHZK). In the leaves of poplars "Lvivska," "Hradizhzka," and "I-45/51," cadmium, one of the highly toxic elements, accumulates 25–30 times more than in the leaves of control plants. High rates of accumulation of heavy metals lead to a violation of the functioning of the plant organism at the physiological and biochemical levels, as evidenced by changes in the content of chlorophyll *a* and *b*. The amount of the main pigments of photosynthesis in the leaves of poplar cultivars under conditions of environmental pollution with heavy metals is lower than in the control, which indicates the inclusion of plant signaling mechanisms. At the same time, the amount of carotenoids in the organs of assimilation of poplars growing on the industrial sites of Northern and Central Iron Ore Dressing Combines (henceforth referred to as Central HZK or CHZK) increases and indicates the realization of their protective functions. The investigated cultivars can be divided into two groups according to the intensity of changes in pigment content. The first group (with a decrease in chlorophylls up to 2 times and an increase in the amount of carotenoids up to 2.5 times) includes "I-45/51," "Lvivska," and "Hradizhzka," and the second group (with a decrease in chlorophylls by more than 2 times and an increase in the amount of carotenoids by more than 2.5 times) includes "Keliberdynska," "Robusta," "Sacrau-59," and "Tronco." This fact indicates better adaptation and greater resistance of cultivars of the first group to the action of heavy metals.

Key words: cultivars of poplars, heavy metals, assimilation apparatus, chlorophylls *a* and *b*, carotenoids.

Introduction

One of the main problems of modern biology is to identify the impact of environmental stresses on plant organisms (Bessonova, Grytsay, 2018; Bessonova, Ponomar'ova, 2017; Fedorchak, 2020, Mareri et al., 2022). Environmental physiology, which has been actively developing recently, deals with the study of adaptive changes and the course of physiological processes that occur under their influence. It is physiological plasticity that determines the prospects for survival and productivity of plants, which is directly related to the use of cultivars resistant to certain stress factors in the national economy (Biswal et al., 2011; Colom, Vazzana, 2001; Correia et al., 2001). In connection with the increase in environmental pollution with heavy metals, there has been a significant increase in the interest in studying their influence on the adaptive capacity and tolerance of plants (Viehweger, 2014; He, 2013). One of the main sources of heavy metals entering the environment is industrial emissions from enterprises of the mining complex. In Europe, the highest concentration of the latter is concentrated in the territory of the Kryvyi Rih Iron Ore Basin. So, the study of the above-mentioned issues in the region becomes even more relevant (Gryshko et al., 2012; Savosko et al., 2022). Poplars (*Populus* L.) belong to fast-growing, highly productive tree species that are widely used in landscaping and national economy (FAO, 1958, 2012, 2016). Due to these features, species of the genus *Populus* L. are the most successful objects among woody vegetation for the study of physiological and biochemical changes that occur in the process of heavy metal intoxication. Recently, there has been an increased interest in the selection of decorative cultivars and tree forms in landscaping areas of various purposes (Biselli et al., 2022; Fuchylo et al., 2017). The detection of taxa, which are the most intensive heavy metal accumulators and tolerant to their action, becomes particularly relevant. Much attention is paid to cultivated forms of plants that are able to actively accumulate and preserve their decorativeness under the influence of heavy metals. However, insufficient attention is paid to the identification of woody plants with a high growth rate and the formation of a powerful biomass

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of assimilating organs, to which the poplar cultivars belong, in Ukraine. Hence, the aim of our work was to conduct research on the clarification of the features of translocation of heavy metals by poplar cultivars with the subsequent establishment of resistance mechanisms at the physiological and biochemical levels of plant organization.

Material and methods

Study area

The study was conducted at three monitoring sites. The monitoring site "Pivnichnyi HZK" (PivnHZK) is located on the territory of Ternivskyi district of the city of Kryvyi Rih near the warehouse for the shipment of finished products of the "Northern Iron Ore Dressing Combine" (48°11'41.2"N 33°31'25.9"E). The topography of the area is flat. The monitoring site "Central HZK" (CHZK) is located on the territory of Pokrovskyi district of the city of Kryvyi Rih near the premises of the production facilities of the ore beneficiation factory of Central Iron Ore Dressing Combine (Myrivske village, the city of Kryvyi Rih, Dnipropetrovsk region) (48°04'43.2"N 33°22' 26.8"E). The topography of the area is flat. The monitoring site "Arboretum of the Kryvyi Rih Botanical Garden of the National Academy of Sciences of Ukraine" (control) is located on the territory of the Ternivskyi district of the city of Kryvyi Rih (48°08'51.5"N 33°34'33.9"E) outside the sanitary protection zone of PivnHZK, at a distance more than 5 km from the source of emissions PivnHZK and at a distance of more than 20 km from the source of emissions CHZK. The topography of the area is flat.

Objects of research

The objects of research were 3-year-old seedlings of seven poplar cultivars that are actively used in the national economy, as well as in landscaping: "Hradizhzka," "I–45/51," "Lvivska," "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco," and the soils on which they grow. Seedlings were grown from lignified cuttings, which were obtained from the mother plant of the Lubny branch of H. M. Vysotskyi National Institute of Forestry and Agromelioration. Two-year-old seedlings were planted at three monitoring sites: in the industrial sites of PivnHZK and CHZK and in the Arboretum of the Kryvyi Rih Botanical Garden of the National Academy of Sciences.

Research methods

Soil samples were taken according to generally accepted methods in soil science from a layer of 0–5 and 10–15 cm (International Organization for Standardization, 2018). Plant material (leaves) was collected in August, after the cessation of shoot growth and the establishment of an apical bud, from the middle part of the crown of 10 individuals of each of the cultivars of the first class according to the age of the southwestern exposure. The content of heavy metals in plant material and soil was determined using methodological guidelines for the determination of heavy metals in soils of agricultural lands and plant products (San PiN 42-128-4433-87, 1988; Hrytsaenko, 2003). Mineralization of plant samples was carried out by the method of dry ashing until complete ashing of the plant material. Acid extraction was performed with nitric acid (1:1 dilution). Further determination of the concentration of heavy metals was carried out using an atomic adsorption spectrophotometer S-115 (Ukraine) according to generally accepted methods (Kochmar, Karabyn, 2022). Determination of the concentration of pigments of the photosynthetic apparatus was carried out by the spectrophotometric method in 100% acetone extract according to Wettstein (Uddin et al., 2020). The optical density of the obtained acetone extract was determined at wavelengths of 662, 644, and 440.5 nm on a spectrophotometer SF-46 (Russia).

Statistical analysis

Calculations of indicators of accumulation of elements of heavy metals in the studied soils were carried out according to formula (1):

$$\sum P^s = Wa/Wb \quad (1),$$

where $\sum P^s$ is the index of element accumulation in the soil, Wa is the gross amount of the element in the tested soil, and Wb is the gross amount of the element in the control soil.

Calculations of indicators of active contamination by heavy metals of the studied soils were carried out according to formula (2):

$$P^s_a = Ca/Cb \quad (2),$$

where P^s_a is an indicator of active soil element contamination, Ca is the number of mobile forms of the element in the studied soil, and Cb is the number of mobile forms of the element in the control soil.

Calculations of soil barrier indicators were carried out according to formula (3):

$$S_b = P^s_a / \sum P^s \quad (3),$$

where S_b is the indicator of the soil barrier.

Calculations of indicators of intratissue pollution of plants were carried out according to formula (4):

$$P^v = Km/Kn \quad (4),$$

where P^v is an indicator of intratissue contamination of plants, Km is the content of the element in the organ in the presence of metal, and Kn is the content of the element in the organ of control plants.

The content of chlorophyll *a* (mg/ml extract) was calculated according to formula (5), chlorophyll *b* according to formula (6), the sum of chlorophylls *a* and *b* according to formula (7), and carotenoids according to formula (8):

$$Ca = 9.784*E_{662} - 0.99*E_{664} \quad (5),$$

$$Cb = 21.426*E_{644} - 4.65*E_{662} \quad (6),$$

$$Ca+b = 5.134*E_{662} - 20.436*E_{664} \quad (7),$$

$$Ccar. = 4.695*E_{440.5} - 0.268*Ca+b \quad (8),$$

where E_{662} is the optical density of the solution at wavelength of 662 nm, E_{644} is the optical density at 644 nm and $E_{440.5}$ is the optical density at 440.5 nm.

Results

Study of translocation of heavy metals in soils

The conducted research made it possible to establish that in the upper layer of the soil of industrial sites near the sources of emissions, the content of mobile forms of ferrum ions in the ammonium acetate extract was more than 2000 times higher than a similar indicator in the soil of a conditionally clean area (Table 1).

An increase in the level of plant-available compounds of copper and zinc (Table 1) and nickel and cadmium (Table 2) was also observed in the technozems of industrial sites. Moreover, the content of copper and zinc ions increased most significantly by 3 times or more. A feature of the distribution of heavy metal compounds extracted by ammonium acetate solution is their greater content in the 0–5 cm soil layer than in the 10–15 cm layer. Thus, in the surface layer (0–5 cm) of technozems of PivnHZK, the amount of zinc was 3.1 times higher than in the 10–15 cm layer where the amount of ferrum, copper, and nickel was 2.8, 1.5, and 1.3 times, respectively.

The obtained data indicate the aerogenic nature of the pollution of industrial sites of enterprises. The arrival of heavy metal compounds with industrial emissions leads to an increase in the content of less-mobile forms of elements in the soil. Thus, the level of ferrum in the soil during extraction by 1 N. HNO_3 solution exceeds the control indicator by 30%, and the levels of copper and nickel exceed by 20–60% (Tables 1, 2). Analysis of the obtained data showed such tendency: the accumulation rate of sedentary forms of heavy metals decreases compared to the accumulation rate of more-mobile forms of the same heavy metals; these more-mobile forms is more available for absorption by plants. Thus, if the content of ferrum ions in the ammonium acetate solution from the soil of industrial sites was 684–2787 times higher than in the control soil, then with the extraction by 1 N. HNO_3 solution, it was only 1.3 times. However, the content of less-mobile forms of lead compounds was 2.6–4.3 times higher than the corresponding control indicator, while the amount of its more accessible compounds for absorption by plants (ammonium acetate solution) did not statistically significantly differ from the control indicator.

Analysis of the results of determination of the content of forms of heavy metals of different mobility in the technozems of the industrial sites of two mining and beneficiation plants in Kryvorizhzhia showed that the level of soil contamination of the industrial site of CHZK was lower than that of PivnHZK. Thus, in the technozems of CHZK, the total number of forms of heavy metals of different mobility was 20–70% less than that in the corresponding soil layers of the northern HZK.

The specified regularity is in good agreement with the results of the gross content of the specified elements. A comparison of the obtained data with the background content of elements in the soils of the Dnipropetrovsk region showed that the content

Table 1. The content of ferrum, copper, and zinc in the soil of monitoring sites located in different ecological conditions, mg/kg of dry soil, $n = 4$.

Place of sampling	Fe		Cu		Zn	
	M±m	V,%	M±m	V,%	M±m	V,%
Ammonium-acetic acid extract						
Control, (A)	0,35±0,03	12,5	0,63±0,03	8,8	4,21±0,31	12,9
Control, (B)	0,35±0,03	12,8	0,22±0,02	12,9	4,66±0,49	18,1
CHZK, (A)	752,09±83,24*	19,2	0,25±0,03*	19,2	5,36±0,20*	6,6
CHZK, (B)	239,50±19,67*	14,2	0,30±0,03*	14,9	5,22±0,04	1,4
PivnHZK, (A)	975,60±9,15*	1,6	1,2±0,03*	4,1	13,15±1,6*	21,0
PivnHZK, (B)	343,79±15,84*	8,0	0,81±0,05*	10,1	4,28±0,27	11,1
Extract 1n HNO_3						
Control, (A)	967,09±8,17	1,5	3,72±0,02	1,0	16,42±1,53	16,1
Control, (B)	1034,72±5,39	0,9	3,59±0,02	0,9	13,68±1,64	20,8
CHZK, (A)	1283,18±79,41*	10,7	3,87±0,01*	0,6	23,29±1,48*	11,0
CHZK, (B)	1013,50±19,61	3,4	5,30±0,04*	1,2	31,75±1,00*	5,5
PivnHZK, (A)	1316,53±11,95*	1,6	4,29±0,2*	8,2	25,66±2,3*	15,5
PivnHZK, (B)	1357,39±9,04*	1,2	4,51±0,21*	8,1	22,58±0,89*	6,8
Gross content						
Control, (A)	2064,89±14,00	1,2	7,78±0,30	6,7	27,91±1,09	6,8
Control, (B)	1227,86±12,88	1,8	7,98±0,17	3,7	17,59±1,77	17,4
CHZK, (A)	2173,01±36,41*	2,9	7,64±0,25	5,6	32,63±0,65*	3,5
CHZK, (B)	1352,73±50,07*	6,4	8,16±0,05	1,1	27,28±0,73*	4,6
PivnHZK, (A)	2200,01±71,69	5,6	8,92±0,2*	3,9	37,45±1,25*	5,8
PivnHZK, (B)	2073,58±79,89*	6,7	8,51±0,13*	2,7	37,46±1,05*	4,8

Notes: A – sampling depth 0–5 cm; B – sampling depth 10–15 cm; *the difference is significant relative to the conditional control, $p \leq 0.05$.

Table 2. The content of nickel, lead and cadmium in the soil of monitoring sites located in different environmental conditions, mg/kg of dry soil, n = 4.

Place of sampling	Ni		Pb		Cd	
	M±m	V,%	M±m	V,%	M±m	V,%
Ammonium-acetic acid extract						
Control, (A)	1,82±0,17	15,7	1,53±0,08	8,8	1,04±0,09	15,4
Control, (B)	1,0±0,02	4,1	1,79±0,18	17,6	0,67±0,07	19,3
CHZK, (A)	2,56±0,03*	1,8	1,65±0,09	9,4	0,80±0,13	28,9
CHZK, (B)	2,02±0,03*	2,8	1,89±0,27	24,9	1,36±0,09*	11,2
PivnHZK, (A)	2,97±0,08*	4,5	1,71±0,06	6,3	1,74±0,12*	11,7
PivnHZK, (B)	2,36±0,08*	5,6	2,02±0,05	3,9	1,45±0,1*	11,4
Extract 1n HNO_3						
Control, (A)	21,12±0,5	4,1	2,03±0,11	9,1	1,07±0,1	15,7
Control, (B)	22,67±0,28	2,1	2,57±0,10	7,0	0,74±0,06	14,3
CHZK, (A)	26,38±0,87*	5,7	5,87±0,60*	17,7	1,22±0,09	12,6
CHZK, (B)	28,92±0,38*	2,3	6,57±0,27*	7,2	0,76±0,07	16,4
PivnHZK, (A)	33,82±1,88*	9,6	8,67±0,44*	8,7	2,09±0,18*	15,3
PivnHZK, (B)	33,48±1,59*	8,2	9,59±0,41*	7,4	1,87±0,16*	14,8
Gross content						
Control, (A)	36,05±1,05	5,0	4,72±0,38	13,9	2,61±0,18	11,7
Control, (B)	36,93±0,48	2,3	5,17±0,37	12,2	2,41±0,07	5,0
CHZK, (A)	36,68±1,62	7,6	9,62±0,48*	8,7	3,72±0,10*	4,5
CHZK, (B)	34,63±1,91	9,5	10,94±0,17*	2,7	2,45±0,10	7,1
PivnHZK, (A)	57,91±2,63*	7,9	10,61±0,56*	9,1	4,48±0,26*	9,9
PivnHZK, (B)	49,74±4,30*	15,0	12,93±0,40*	5,3	2,74±0,14*	8,6

Notes: A – sampling depth 0–5 cm; B – sampling depth 10–15 cm; *the difference is significant relative to the conditional control, $p \leq 0.05$.

of nickel and cadmium in the technozems of industrial sites was 3.4–5.8 times higher than the background values (10 and 1.0 mg/kg of soil, respectively). The level of accumulation of gross forms of copper, nickel, cadmium, and lead exceeded the average values for arable lands of the region. The most significant excess (18.3 times) was recorded for cadmium. Despite the excess of the content of heavy metals observed in the soils of industrial sites of mining and beneficiation enterprises compared to their background content in the soils of the region, it should be noted that only cadmium was characterized by a statistically significant excess (by 1.4 times) of the values of the maximum allowable concentrations of elements in soils.

To assess the buffer capacity of soils at different levels of pollution, relative indicators were used, taking into account both the gross content of polluting elements and the number of their mobile forms (Gryshko et al., 2012). According to the obtained data, the highest relative indicators of the accumulation of elements in the soils of polluted areas are characteristic of lead and cadmium (Fig. 1).

Intensive contamination of technozems with compounds of copper, zinc, nickel, and cadmium (1.7–3.1) indicates a high degree of supply of these elements to food chains of man-made ecotopes.

As a result of the research, it was found that the most toxic elements (lead and cadmium), which have high rates of relative accumulation in the soil of industrial sites, are characterized by the lowest ($\sum P^s$ = 0.6–0.8) ability to accumulate in less-mobile forms, that is, the soil barrier for these elements functions less effectively.

Research on the accumulation of heavy metals in the assimilation apparatus of poplar cultivars

The study results showed that the translocation of ferrum ions in the assimilation organs of "Hradizhzka," "I–45/51," and "Lvivska" occurs most intensively, the level of accumulation of which in the above-mentioned cultivars at the industrial site of CHZK exceeded the indicators for the conditional control by up to 20 times (Table 3). Under conditions of heavy pollution, similar trends are observed.

Iron compounds were most significantly accumulated in the assimilation organs of "Hradizhzka" (the value of the index of intratissue contamination of the leaf was 22.0). At the same time, in the assimilation organs of the above-mentioned cultivars growing in conditions with different levels of pollution, in terms of absolute values, ferrum ions accumulated 2.8–10 times more than in "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco" (Table 3).

High level of translocation of cadmium, which is a highly toxic element, under conditions of severe pollution was characteristic of cultivars "Hradizhzka" (indicator of intratissue pollution of the leaf was 26.0) and "Lvivska" (25.1). The highest index of cadmium contamination (30.7) was found for cultivar "I–45/51". The obtained data agree well with the values of the absolute content of the element.

Thus, in the organs of assimilation of the above-mentioned poplar cultivars, under conditions of moderate pollution, cadmium ions accumulate 1.8–19.6 times, and with strong pollution,

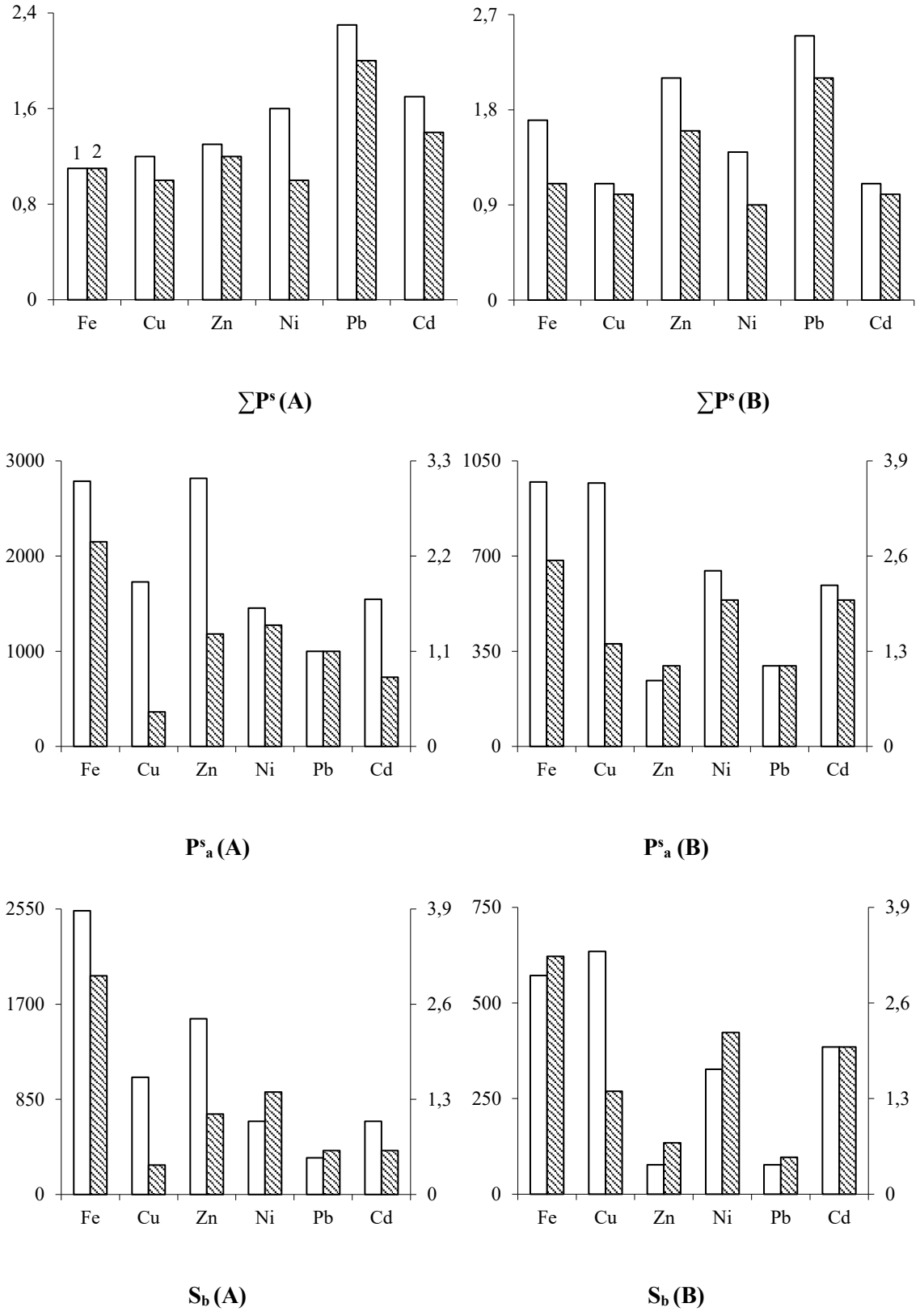


Fig. 1. Values of indicators of soil contamination by heavy metals in different environmental conditions. 1 – CHZK, 2 – PivnHZK, (A) – sampling depth 0–5 cm, (B) – sampling depth 10–15 cm, $\sum P^s$ – accumulation index of an element in the soil, P^s_a – indicator of active soil pollution, S_b – soil barrier.

Table 3. Accumulation of some heavy metals in the assimilation organs of poplar cultivars growing in different environmental conditions.

Place of sampling	Fe		Cu		Zn		Ni		Pb		Cd	
	M±m	P^v	M±m	P^v	M±m	P^v	M±m	P^v	M±m	P^v	M±m	P^v
1	2	3	4	5	6	7	8	9	10	11	12	13
'Hradizhzka'												
Control	440,3±25,42		8,3±0,73		77,6±3,61		15,2±0,54		20,6±1,79		12,9±0,70	
CHZK	8181,3±407,43*	18,6	36,8±1,15*	4,4	379,4±28,45*	4,9	111,5±7,57*	7,4	165,7±15,39*	8	199,8±7,81*	15,5
PivnHZK	9706,7±680,91*	22	101,1±4,10*	12,1	641,6±39,40*	8,3	213,5±14,91*	14,1	233,6±14,55*	11,3	335,8±27,06*	26
'I–45/51'												
Control	416,0±18,48		7,1±0,38		85,6±4,58		9,5±0,48		14,3±0,57		6,4±0,28	
CHZK	6080,0±369,50*	14,6	22,0±0,93*	3,1	293,6±19,92*	3,4	63,3±3,07*	6,7	157,7±10,34*	11	80,1±3,54*	12,5
PivnHZK	7232,0±387,98*	17,4	57,8±5,13*	8,2	686,6±52,92*	8	124,5±10,39*	13,1	186,3±14,55*	13	197,3±10,48*	30,7
'Lvivska'												
Control	394,7±38,46		6,8±0,25		91,6±8,66		8,2±0,28		16,1±1,52		5,8±0,18	
CHZK	6336,0±337,14*	16,1	37,4±2,33*	5,5	329,6±16,09*	3,6	44,5±1,80*	5,5	150,8±10,19*	9,4	75,3±3,91*	13
PivnHZK	7360,0±369,50*	18,6	63,1±3,48*	9,3	795,6±30,51*	8,7	126,0±7,94*	15,5	193,5±5,53*	12,1	145,3±11,46*	25,1
'Sacrau-59'												
Control	240,0±8,05		7,3±0,29		30,6±2,65		6,6±0,33		3,4±0,50		1,5±0,07	
CHZK	816,0±51,23*	3,4	12,3±0,82*	1,7	63,2±3,03*	2,1	19,4±1,00*	3	24,7±1,60*	7,2	3,2±0,21*	2,1
PivnHZK	1734,4±99,35*	7,2	18,9±1,15*	2,6	83,6±7,81*	2,7	40,0±3,28*	6,1	33,0±1,74*	9,6	12,8±0,61*	8,6
'Keliberdynska'												
Control	320,0±16,93		4,0±0,12		49,6±3,46		15,9±0,71		3,4±0,50		8,4±0,46	
CHZK	1589,3±136,18*	5	4,9±0,17*	1,2	141,6±6,56*	2,9	29,8±1,66*	1,9	6,3±0,29*	1,8	42,3±1,32*	5
PivnHZK	2613,3±136,18*	8,2	7,2±0,21*	1,8	204,6±5,57*	4,1	57,1±2,12*	3,6	10,6±0,76*	3,1	52,8±3,61*	6,3
'Robusta'												
Control	280,5±11,14		4,3±0,29		27,8±1,51		7,2±0,33		2,0±0,29		4,9±0,30	
CHZK	1834,7±38,46*	6,5	15,9±1,17*	3,7	58,6±3,46*	2,1	18,0±0,35*	2,5	6,6±0,29*	3,3	14,7±0,58*	3
PivnHZK	2026,7±56,44*	7,2	19,5±0,80*	4,5	159,6±11,53*	5,7	33,6±2,18*	4,7	12,9±0,99*	6,4	32,8±2,25*	6,7
'Tronco'												
Control	139,7±7,47		4,4±0,32		40,1±2,18		4,1±0,17		2,0±0,29		5,7±0,48	
CHZK	1077,3±28,22*	7,7	7,3±0,73*	1,7	88,7±6,15*	2,2	6,4±0,48*	1,6	4,0±0,29*	2	10,2±0,57*	1,8
PivnHZK	1301,3±21,33*	9,3	10,4±0,33*	2,4	110,6±5,57*	2,8	10,1±0,51*	2,5	6,3±0,57*	3,1	35,9±3,38*	6,3

Notes: P^v – the value of the index of intratissue contamination of the leaf; *the difference is significant relative to the control, $p \leq 0.05$.

2.8–10.2 times more than in "Keliberdynska," "Robusta," and "Tronco" (Table 3). "Sacrau-59" accumulates the least amount of cadmium in the conditions of all variants of the experiment, and the least amount of zinc is translocated to its assimilation organs. If in "Hradizhzka," "I–45/51," and "Lvivska," the values of the index of intratissue zinc contamination range from 3.4 to 8.7, then for "Sacrau-59," it is 2.4 on average.

A comparison of the obtained data on the index of intratissue contamination of the leaf with zinc showed that on the industrial site of the CHZK cultivars "Hradizhzka," "I–45/51," and "Lvivska," it is on average 1.7 times higher, and at PivnHZK, it is 2.2 times higher, than in "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco." Among the elements less toxic to the environment, copper and nickel ions are intensively translocated to the leaves of poplar cultivars.

Moreover, nickel was most actively accumulated in the conditions of the ore processing enterprise of PivnHZK in "Lvivska," and copper compounds in the assimilation organs of "Hradizhzka," while for "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco," the values of indicators of intratissue contamination of leaves under similar growth conditions were 2–7 times smaller (Table 3).

Despite the fact that the supply of lead ions to plants is to a greater extent aerogenic, namely, from gaseous emissions of motor vehicles, the translocation trends of the specified toxicant among the studied cultivars are preserved. Thus, the index of intratissue contamination of the leaf with the above-mentioned element in "Hradizhzka," "I–45/51," and "Lvivska" under conditions of moderate contamination is 2.4–6.1 times more, and under conditions of severe contamination is 1.8–4.2 times larger than "Keliberdynska," "Robusta," and "Tronco."

So, when finding out the intensity of translocation of heavy metals by poplar cultivars at different levels of environmental pollution, data were obtained that allow us to divide the research plants into two groups. The first group included "Hradizhzka," "I–45/51," and "Lvivska" (with high level of metal translocation by assimilation organs), and the second one included "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco" (with low level of metal translocation by assimilation organs).

Study of quantitative changes of pigments in the assimilation apparatus of poplar cultivars

As mentioned earlier, the signal response of quantitative changes in chlorophyll *a*, which plays a leading role in the absorption of light quanta (Getko, 1989; Podobed, 2008), under the action of heavy metals can be evidence of different levels of plant adaptation. During field experiments, it was established that the content of chlorophyll *a* in the assimilation apparatus of "Tronco," "Keliberdynska," "Sacrau-59," and "Robusta" at the industrial sites of CHZK and PivnHZK was 1.5–2.1 times lower than in plants of conventional control, while for other cultivars - only in 10–35% (Table 4).

Other components of the pigment system play a significant role in the ecological lability of the photosynthesis process: chlorophyll *b* and carotenoids (Siedlecka, Krupa, 1996; Stoyanova et al., 2004).

Research has established that in the assimilation organs of poplar cultivars on the industrial site of CHZK, at a low level of pollution by heavy metals, the amount of chlorophyll *b* decreases most intensively (by 1.3–1.6 times) in the cultivars "Tronco," "Keliberdynska," "Sacrau-59," and "I–45/51" (Table 4). In conditions of heavy pollution, the same tendency is observed for "Lvivska" and "Robusta." Similar regularities are observed for the content of the sum of chlorophylls *a* and *b*.

As mentioned earlier, carotenoids perform a protective function in the pigment system of the plant organism. In the adaptation process of the assimilation organ at the physiological level, carotenoids protect chlorophylls from oxidation, which contributes to the course of normal growth processes in poplars and testifies to their resistance to the action of heavy metals.

The study of the amount of carotenoids made it possible to establish that their content in poplar cultivars under polluted conditions is statistically significantly higher than in the control. Analy-

Table 4. The number of pigments in the assimilation organs of poplar cultivars in conditions of pollution by heavy metals, mg/g of raw substance.

Cultivars of poplars	Control	CHZK	PivnHZK
Chlorophyll *a*			
'Tronco'	0,144±0,0017	0,084±0,0010*	0,068±0,0008*
'Sacrau-59'	0,159±0,0048	0,098±0,0030*	0,087±0,0026*
'Robusta'	0,167±0,0025	0,109±0,0017*	0,097±0,0015*
'Keliberdynska'	0,156±0,0033	0,091±0,0019*	0,073±0,0016*
'Lvivska'	0,222±0,0024	0,157±0,0017*	0,148±0,0016*
'I–45/51'	0,325±0,0040	0,301±0,0036*	0,275±0,0033*
'Hradizhzka'	0,224±0,0023	0,156±0,0016*	0,148±0,0015*
Chlorophyll *b*			
'Tronco'	0,356±0,0032	0,225±0,0020*	0,191±0,0017*
'Sacrau-59'	0,356±0,0045	0,262±0,0030*	0,228±0,0026*
'Robusta'	0,362±0,0067	0,288±0,0051*	0,248±0,0044*
'Keliberdynska'	0,342±0,0075	0,217±0,0047*	0,197±0,0041*
'Lvivska'	0,455±0,0050	0,356±0,0039*	0,303±0,0033*
'I–45/51'	0,576±0,0047	0,419±0,0036*	0,391±0,0033*
'Hradizhzka'	0,557±0,0025	0,479±0,0022*	0,404±0,0018*
Sum of chlorophylls *a* and *b*			
'Tronco'	0,500±0,0016	0,309±0,0010*	0,259±0,0009*
'Sacrau-59'	0,515±0,0017	0,359±0,0011*	0,315±0,0010*
'Robusta'	0,529±0,0044	0,397±0,0035*	0,345±0,0030*
'Keliberdynska'	0,498±0,0066	0,308±0,0041*	0,269±0,0036*
'Lvivska'	0,677±0,0073	0,513±0,0056*	0,451±0,0049*
'I–45/51'	0,902±0,0062	0,720±0,0050*	0,666±0,0046*
'Hradizhzka'	0,781±0,0037	0,635±0,0030*	0,552±0,0026*
Sum of carotenoids			
'Tronco'	0,156±0,0068	0,439±0,0124*	0,568±0,0152*
'Sacrau-59'	0,176±0,0044	0,407±0,0067*	0,513±0,0080*
'Robusta'	0,190±0,0027	0,425±0,0034*	0,538±0,0038*
'Keliberdynska'	0,174±0,0045	0,440±0,0064*	0,543±0,0073*
'Lvivska'	0,213±0,0034	0,415±0,0037*	0,511±0,0039*
'I–45/51'	0,240±0,0051	0,337±0,0053*	0,400±0,0056*
'Hradizhzka'	0,233±0,0021	0,405±0,0023*	0,516±0,0024*

Note: *The difference is significant relative to the conditional control, $p \leq 0.05$.

sis of the obtained results revealed that the amount of carotenoids in the assimilation apparatus of "Tronco," "Robusta," "Keliberdynska," and "Sacrau-59" at the industrial sites of CHZK and PivnHZK is more than 2.5 times higher than in the conditional control.

Discussion

Analysis of the results of determination of the content of forms of heavy metals of different mobility in the technozems of the industrial sites of two mining and beneficiation plants in Kryvorizhzhia shows that the level of soil contamination of the industrial site of CHZK is lower than that of PivnHZK. Thus, in the technozems of CHZK, the total number of forms of heavy metals of different mobility was 20–70% less than in the corresponding soil layers of PivnHZK. As a result of the research, it was found that the most toxic elements (lead and cadmium), which have high rates of relative accumulation in the soil of industrial sites, are characterized by the lowest (S_b = 0.6–0.8) ability to accumulate in less-mobile forms, that is, the soil barrier for these elements functions less effectively. When investigating the intensity of translocation of heavy metals by poplar cultivars at different levels of environmental pollution, data were obtained that allow us to divide the experimental plants into two groups. The first group included "Hradizhzka," "I–45/51," and "Lvivska" (with high level of metal translocation by the assimilation organs), and the second group included "Sacrau-59," "Keliberdynska," "Robusta," and "Tronco" (with a low level).

As a result of the research, the following conclusions can be drawn. The amount of the main pigments of photosynthesis in the assimilation apparatus of poplar cultivars under conditions of environmental pollution with heavy metals is lower than in the conditional control, which indicates the inclusion of plant signaling mechanisms. At the same time, the amount of carotenoids in the organs of assimilation of poplars growing on the industrial sites of PivnHZK and CHZK increases and indicates realization of their protective functions. The investigated cultivars can be divided into two groups according to the intensity of changes in pigment content. The first group (with a decrease in chlorophylls up to 2 times and an increase in the amount of carotenoids up to 2.5 times) includes "I-45/51," "Hradizhzka," and "Lvivska;" the second one (with a decrease in chlorophylls more than 2 times and an increase in the amount of carotenoids more than 2.5 times) includes "Keliberdynska," "Tronco," "Sacrau-59," and "Robusta." This fact indicates better adaptation and greater resistance of cultivars of the first group to the action of heavy metals compared to cultivars of the second group.

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